

447
FLOW OF STEAM ,

...THROUGH...

Long, Narrow, Rectangular Ports,

...BY...

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THESIS:

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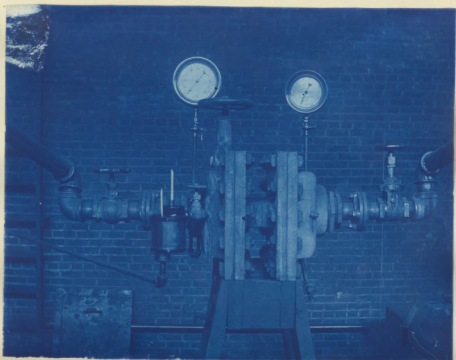
VELOCITY OF STEAM THROUGH LONG NARROW RECTANGULAR PORTS.

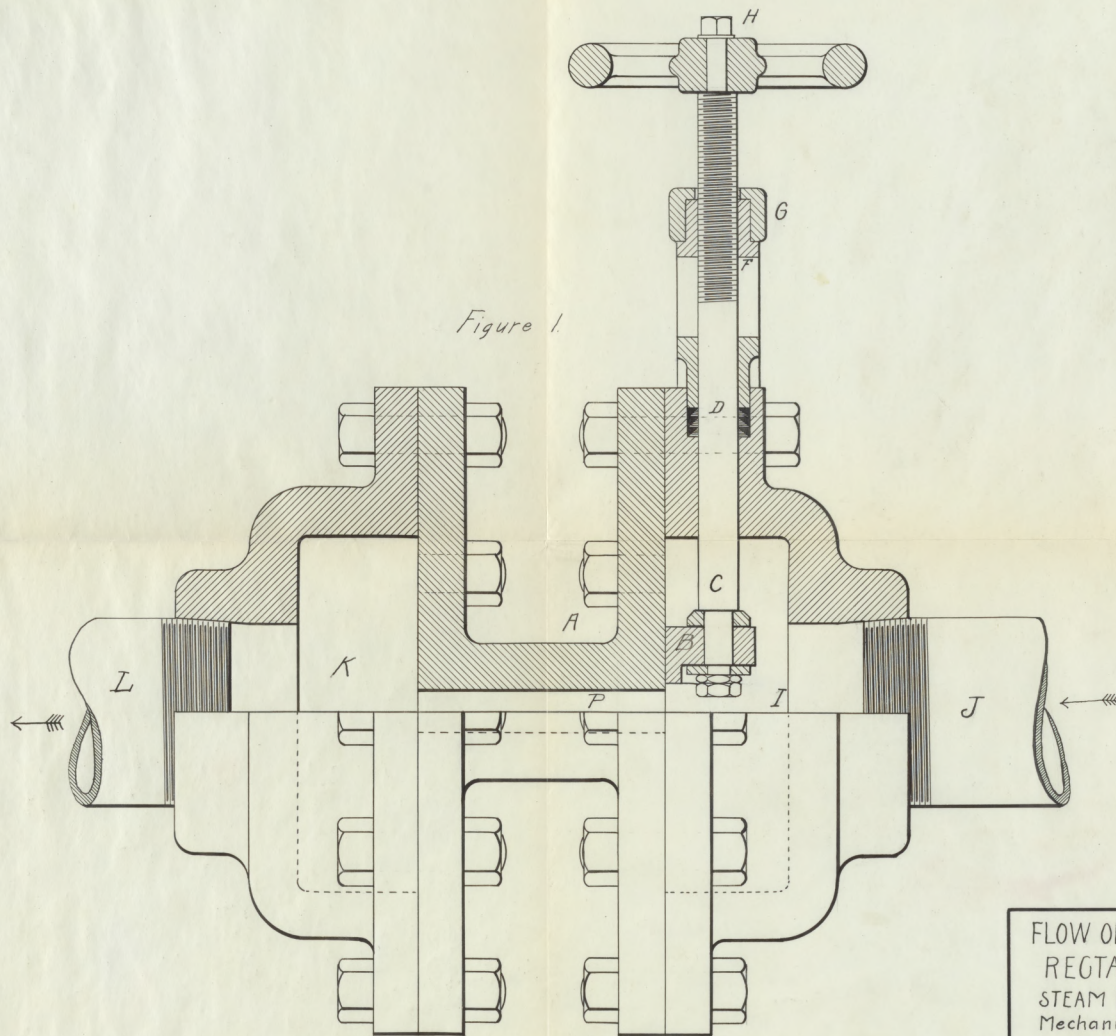
The following experiments were made at the Central Heating plant at the University of Illinois, to determine the velocity of steam flowing through long narrow rectangular ports; when the opening is regulated by a plain slide valve. The apparatus used in these experiments was designed to give as nearly as possible the same conditions that obtain in steam engines of the D valve type.

The apparatus is shown in the blue print page 2, as it was mounted for experimenting on the bridge connecting the multitubular and National water^{tube} boilers. It is designed to withstand two hundred pounds steam pressure and the pattern making, moulding, machining and erection was done by myself.

The drawing page 3 shows the apparatus in detail. It consists of a casting A, with a rectangular port P, 1 x 10 inches and 6 inches long, passing through the center. It is closed and opened by a plain slide valve B, operated by valve rod C. The rod C passes through a stuffing box at D and is threaded with $\frac{1}{8}$ inch pitch so that one complete revolution of hand wheel H, will open or close the port $\frac{1}{8}$ of an inch. The thread engages in a brass nut F, which is securely fastened to the yoke G.

Steam from the boiler entered through a 2 inch globe valve in steam pipe J, into chamber I, which has the same function as the steam chest of an engine. It then passed through port P, into chamber K, which acts as the engine cylinder. From there it was conducted through a 2 inch gate valve in steam pipe L, to the low pressure heating main. The pressure in the steam chest was observed by the





FLOW OF STEAM THROUGH
 RECTANGULAR PORTS
 STEAM PORT APPARATUS
 Mechanical Engineering Dept.
 University of Illinois
 THESIS DRAWING
 Scale $\frac{1}{2}$

W. A. Fraser May 1899

left hand gage in the blue print and the pressure was maintained constant by means of the globe valve in pipe J. This was easily accomplished and could be done no matter how the pressure in the boiler varied, as long as it was about seventy-five pounds.

The exhaust pressure was observed on the right hand gage in the blue print and was kept constant during an experiment by operating the gate valve in pipe L.

The initial steam pressure in all the experiments was sixty pounds; that being the highest pressure that could be maintained during the experiments. Fifteen different experiments were all that could be obtained with the boiler used.

The 100 horse power multitubular boiler in the Central heating plant was used to furnish the steam for the experiments. The apparatus as shown in the blue print was connected to the boiler main by about four feet of two inch pipe and had an angle globe valve at the point where it was connected with the steam main.

The exhaust pipe was two inches in diameter and entered the low pressure heating main through a two and one-half inch angle globe valve.

The quality of the steam was determined by a universal steam Barus calorimeter, '95 pattern, which was connected with the steam chest as shown on the left of the blue print. Temperature readings were taken every five minutes unless the fluctuation was too great, when a reading was taken whenever the temperature changed more than five degrees.

The weight of the steam flowing was determined by reading the height of the water on the glass gage at the beginning and end of

an experiment and finding the weight of water used from a calibration curve for the boiler, then making corrections to this weight for moisture in the steam and for the weight of the steam that passed out through the calorimeter. All of the experiments were of from fifteen to thirty minutes duration. Before taking an experiment, steam was allowed to flow through the apparatus for at least ten minutes and the water from the chambers was completely drawn off through the drip cocks. This was to eliminate all errors due to the condensation and to insure uniform conditions during an experiment.

The data for the calibration curve was obtained by filling the boiler with water to within one inch of the top of the gage glass and weighing it out one inch at a time, down to the bottom of the glass. The height of the water was read on a seasoned oak scale, graduated to tenths of inches, which was placed beside the gage glass.

The curve Figure 2 was plotted from this data, with inches on the scale as abscissa and hundred pounds of water as ordinates. It covers the range through which the height of water changed during the experiments. The curve in figure two was used in determining the weight of steam for the experiments. Before beginning an experiment the boiler was filled up to within about three inches of the top of the gage glass and after the pressure was raised sufficiently the steam was allowed to flow through the apparatus. The height of the water was read at the beginning and end of the experiment. No water was put into the boiler during an experiment and all opening aside from the port were tightly closed, so that no steam could

escape from the boiler without going through the apparatus.

Experiments were made with port openings of $\frac{1}{16}$, $\frac{1}{8}$, $\frac{3}{16}$ and $\frac{1}{4}$ inches. The experiments with the $\frac{1}{16}$ inch opening were taken with sixty pounds steam chest pressure and a drop in pressure on the exhaust side of from five to forty-five pounds in steps of five pounds; making in all eight experiments. For $\frac{1}{8}$ inch port opening the experiments were taken with an initial pressure of sixty pounds and dropped five to twenty pounds; four experiments in all. With the $\frac{3}{16}$ inch port opening only two experiments could be taken with a steam chest pressure of sixty pounds and exhaust pressures of fifty-five and fifty pounds. One experiment with the $\frac{1}{4}$ inch port opening with an initial pressure of sixty pounds, exhausting against fifty-five pounds was all that the boiler would furnish steam for. For the same port opening and back pressure five or more experiments were taken making eighty in all. The mean of five was taken as the result.

The following form of logs were kept during the experiment:

$\frac{1}{8}$ " Time	Log of Experiment No. 1.				Tem. in Calorimeter Ther. No. 2.
	Initial Pressure in Pounds	Exhaust Pressure in Pounds	Height of Water in Gage Glass in Inches	Ther. No. 1	
10-45	60	40	2.7	224	294
10-50	60	40		228	294
10-55	60	40		231	296
11-00	60	40		236	296
11-05	60	40		240	298
11-10	60	40		238	300
11-15	60	40	10.9	243	300

By means of the calibration curve the weight of water evaporated per minute was obtained. This weight corrected for moisture and the steam passing through the calorimeter gives the pounds of steam passing through the port in one minute. The area of the port being known and the volume of the steam being calculated for the pressure; the velocity

$$w = \frac{W}{AD}$$

Where w = velocity in feet per minute.

W = weight of steam passing per minute in pounds.

A = area of port opening in square feet.

D = weight of steam per cubic foot.

THEORETICAL VELOCITY OF STEAM PASSING THROUGH AN ORIFICE.

When steam flows through an orifice like a port, heat is neither added nor extracted and the expansion follows the adiabatic curve and there is a gradual change of pressure from p to p_1 where p_1 is the lower pressure.

The volume also changes with the pressure from v to v_1 .

The work of the molecules is.

$$L = \frac{q - q_1 + x\rho - x_1\rho_1}{A} I$$

q & q_1 = Heat units required to raise the temperature of the water from 32° to the temperature of the steam at p & p_1 pressures.

ρ = Inner latent heat.

x & x_1 = Quality of the steam.

The numerator is the heat disappearing during expansion, which is equal to AL .

A = mechanical equivalent of heat.

L = outer work.

The pressure of the steam in the boiler exerts a force which not only overcomes the pressure on the outside of the orifice but it also imparts a velocity to the steam. If w = velocity of the steam

$$pv = \frac{w^2}{2g} + p_1v_1 \quad II$$

Where pv = work expended to force steam out of orifice and give it velocity w .

To this work must be added the work equivalent of the heat disappearing during expansion.

Then

$$pv - p_1v_1 + \frac{q - q_1 + x\rho - x_1\rho_1}{A} = \frac{w^2}{2g} \quad III$$

Multiplying both sides by A and putting $v = x\mu + \sigma$ and $v_1 = x_1\mu_1 + \sigma$

$\mu \text{ \& } \mu_1 = (s - \sigma)$ s = specific steam volume, σ = specific water volume.

$$q + x\rho + A\mu x - (q_1 + x_1\rho_1 + A\mu_1 x_1) + A\sigma(p - p_1) = A \frac{w^2}{2g} \quad \text{IV}$$

$A\sigma(p - p_1)$ is so small that it can be disregarded.

$$\rho + A\mu = r$$

$A\mu$ = outer latent heat.

r = total latent heat.

ρ = inner latent heat.

Substituting these values in IV.

$$A \frac{w^2}{2g} = q - q_1 + xr - x_1 r_1 \quad \text{V}$$

$$w = \sqrt{\frac{2g}{A} (q - q_1 + xr - x_1 r_1)} \quad \text{VI}$$

$$\frac{1}{A} = 772 \quad 2g = 32.2$$

$$w = 222.8 \sqrt{q - q_1 + xr - x_1 r_1} \quad \text{VII}$$

Since p , p_1 and x are known.

q , q_1 , r and r_1 can be found in table.

$$x_1 = \frac{r - r_1 + \frac{xr}{T}}{\frac{r_1}{T_1}}$$

T and $\frac{xr}{T}$ are given in the table.

From formula VII the theoretical velocity of saturated steam and steam with two percent moisture were calculated and the results are given on the following pages.

The data and results of the experiments are given in the following tables:

Table 1. pp 13 gives the velocity of steam calculated for theoretical flow and from the data obtained by experiment the results above and to the left of the double lines were obtained by experiment while those to the right were taken from the curves drawn by comparison with the ones plotted from the experimental results.

Table 2. pp 14 to 19 gives the results as obtained by experiment.

The curves Figures 3 to 9 were plotted from the results of the experiments and are explained on each diagram.

An inspection of the curves Figures 4 to 9 shows that there is a marked change in the velocity of the steam when the exhaust pressure falls to between forty and thirty-five pounds. *for a 1/16" port opening the velocity for, from fifty-five to thirty-five pounds exhaust pressure can be approximately calculated by the formula*

$$w = 345 \sqrt{H}$$

w = velocity in feet per minute.

H = height in feet of a column of steam, of the pressure of the steam in the steam chest, which would produce a pressure equal to the difference of pressure on the two sides of the port.

For each one-sixteenth inch increase in the port opening the velocity increases about four per cent.

When the exhaust pressure falls below thirty-five pounds there is but a slight increase in the velocity and for a formula there would have to be a change in the constant for each change

in the exhaust pressure.

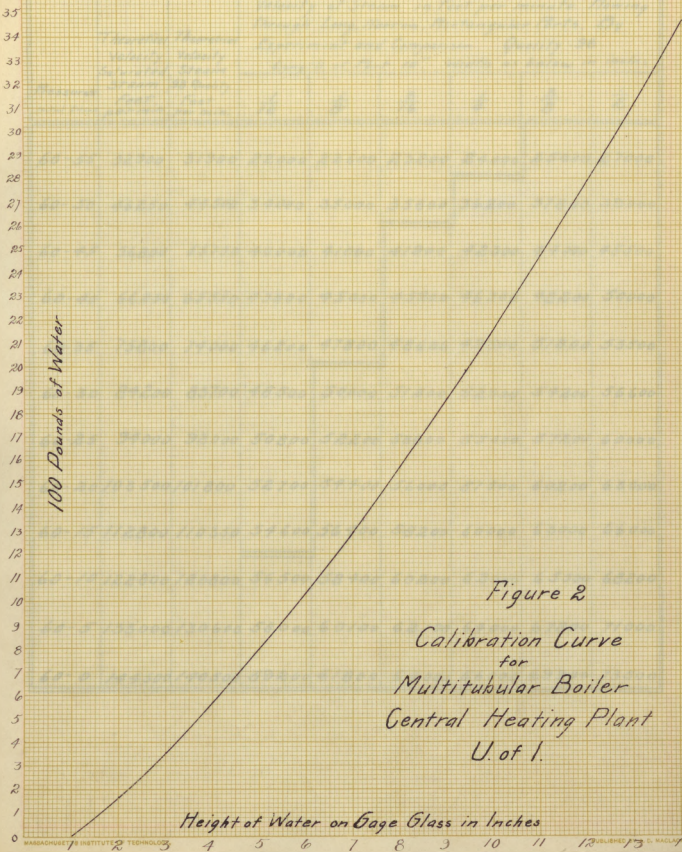


Figure 2
Calibration Curve
for
Multitubular Boiler
Central Heating Plant
U. of I.

Table No. 1.

Pressures Initial Exhaust	Theoretical Velocity Saturated Steam Feet per min	Theoretical Velocity Steam 98 Quality Feet per min	Velocity of Steam in feet per minute Flowing through Long, Narrow, Rectangular Ports. By Experiment and Comparison Quality .98 Length of Port 10" Width as below in inches					
			$\frac{1}{16}$	$\frac{1}{8}$	$\frac{3}{16}$	$\frac{1}{4}$	$\frac{3}{8}$	$\frac{1}{2}$
60-55	32900	31900	22000	22600	23200	24000	25000	27000
60-50	46250	44500	34000	35000	35800	36200	37800	39000
60-45	56800	55750	40000	41000	41900	42300	44000	45500
60-40	66250	65500	43800	45000	45900	46300	48200	50000
60-35	75800	74000	46200	47800	48600	49500	51200	53500
60-30	84200	83700	48500	50000	51200	52300	54200	56600
60-25	94000	92000	50800	52200	53800	55000	57200	60000
60-20	103500	101800	52700	54400	56000	57500	60200	63000
60-15	112800	110350	54600	56400	58200	60000	63000	66000
60-10	122800	120800	56500	58400	60200	62000	65500	68200
60-5	133000	130600	58000	60100	62100	64000	67800	71000
60-0	144500	140500	59200	61800	64000	66000	69900	73500

Table No. 2.

Experiment No.	Port Opening inches	Pressure Exhausted Against pounds	Quality of Steam	Weight of Water Evaporated per min.	Weight of Steam passing through Port per min.	Velocity in Feet per min.
1	$\frac{1}{16}$	55	.9855	18	17.34	22838
2	$\frac{1}{16}$	55	.9817	17	16.29	21452
3	$\frac{1}{16}$	55	.9839	18	17.31	22798
4	$\frac{1}{16}$	55	.9833	18	17.30	22785
5	$\frac{1}{16}$	55	.9805	16	15.29	20135
6	$\frac{1}{16}$	50	.9818	26	25.52	33200
7	$\frac{1}{16}$	50	.9789	26	25.45	33050
8	$\frac{1}{16}$	50	.9817	29	28.08	36980
9	$\frac{1}{16}$	50	.9827	27	26.73	34300
10	$\frac{1}{16}$	50	.9811	28	27.07	35653
11	$\frac{1}{16}$	45	.9800	32.5	31.41	41350
12	$\frac{1}{16}$	45	.9802	32	30.96	40780
13	$\frac{1}{16}$	45	.9808	32	30.98	40800
14	$\frac{1}{16}$	45	.9811	32.5	31.48	41450

Table No. 2 con.

Experi- ment No.	Port Opening inches	Pressure Exhausted Against Pounds	Quality of Steam	Weight of Water Evaporated per min	Weight of Steam pas- sing through Port per min	Velocity in Feet per min.
15	$\frac{1}{16}$	45	.9800	31.5	30.77	40200
16	$\frac{1}{16}$	40	.9805	33.5	32.45	42734
17	$\frac{1}{16}$	40	.9802	34	32.93	43360
18	$\frac{1}{16}$	40	.9805	34.5	33.43	44025
19	$\frac{1}{16}$	40	.9824	34	33.	43460
20	$\frac{1}{16}$	40	.9802	34	32.93	43360
21	$\frac{1}{16}$	35	.9824	34	33	43460
22	$\frac{1}{16}$	35	.9786	35	33.85	44600
23	$\frac{1}{16}$	35	.9800	35	33.90	44650
24	$\frac{1}{16}$	35	.9820	37	35.93	47320
25	$\frac{1}{16}$	35	.9911	37	36.67	48100
26	$\frac{1}{16}$	30	.9942	37.5	36.93	48640
27	$\frac{1}{16}$	30	.9811	38.	37.28	49100
28	$\frac{1}{16}$	30	.9795	37.0	35.84	47200
29	$\frac{1}{16}$	30	.9800	37.5	36.31	47820

Table No. 2 con.

Experi- ment No.	Port Opening Inches	Pressure Exhausted Against Pounds	Quality of Steam	Weight of Water Evaporated per min.	Weight of Steam pas- sing through per min.	Velocity in Feet per min.
30	$\frac{1}{16}$	30	.9786	37.5	36.30	47805
31	$\frac{1}{16}$	25	.9800	40.	38.79	51090
32	$\frac{1}{16}$	25	.9811	39.5	38.75	50800
33	$\frac{1}{16}$	25	.9802	40.5	39.30	51750
34	$\frac{1}{16}$	25	.9789	41.	39.73	52330
35	$\frac{1}{16}$	25	.9930	39.25	38.56	50780
36	$\frac{1}{16}$	20	.9910	40.75	39.98	52660
37	$\frac{1}{16}$	20	.9824	40.30	39.23	51670
38	$\frac{1}{16}$	20	.9862	40.50	39.54	52080
39	$\frac{1}{16}$	20	.9848	42.25	41.20	54270
40	$\frac{1}{16}$	20	.9848	41.20	40.17	52912
41	$\frac{1}{16}$	15	.9896	42.25	41.41	54540
42	$\frac{1}{8}$	55	.9808	34.5	33.44	22020
43	$\frac{1}{8}$	55	.9814	34	32.96	21700
44	$\frac{1}{8}$	55	.9811	35	33.94	22350

Table No. 2 con.

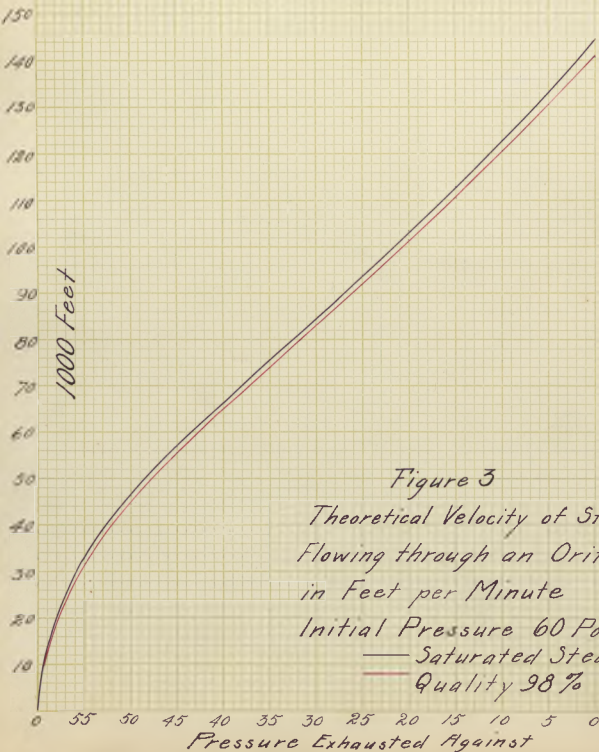
Experi- ment No.	Port Opening inches	Pressure Exhausted Against pounds	Quality of Steam	Weight of Water Evaporated per min.	Weight of Steam per Port per min.	Velocity in Feet per min.
45	$\frac{1}{8}$	55	.9808	37.00	35.89	23634
46	$\frac{1}{8}$	55	.9800	36.25	35.12	23130
47	$\frac{1}{8}$	50	.9783	52.00	50.47	33230
48	$\frac{1}{8}$	50	.9805	52.00	50.59	33320
49	$\frac{1}{8}$	50	.9805	58.00	56.47	37190
50	$\frac{1}{8}$	50	.9808	57.50	56.00	36870
51	$\frac{1}{8}$	50	.9800	57.00	55.86	3600
52	$\frac{1}{8}$	45	.9814	71.50	69.77	41945
53	$\frac{1}{8}$	45	.9800	71.50	69.67	41800
54	$\frac{1}{8}$	45	.9786	71.00	69.03	41200
55	$\frac{1}{8}$	45	.9800	70.00	68.19	40800
56	$\frac{1}{8}$	45	.9800	69.50	68.00	40650
57	$\frac{1}{8}$	40	.9827	70.50	68.87	45350
58	$\frac{1}{8}$	40	.9811	75.50	73.78	48580
59	$\frac{1}{8}$	40	.9827	70.00	68.50	44900

Table No. 2 con

Experiment No.	Port Opening Inches	Pressure Exhausted Against Pounds	Quality of Steam	Weight of Water Evaporated per min.	Weight of Steam passing through per min.	Velocity in feet per min.
60	$\frac{1}{8}$	40	.9811	75.50	73.78	48580
61	$\frac{1}{8}$	40	.9780	72.00	70.02	46110
62	$\frac{1}{8}$	40	.9893	71.50	70.30	46620
63	$\frac{1}{8}$	35	.9910	73.00	71.95	47414
64	$\frac{1}{8}$	35	.9810	75.00	73.10	48420
65	$\frac{1}{8}$	35	.9890	72.00	71.21	47000
66	$\frac{3}{16}$	55	.9796	49.50	48.09	23110
67	$\frac{3}{16}$	55	.9793	50.00	48.60	23340
68	$\frac{3}{16}$	55	.9793	48.00	46.60	22460
69	$\frac{3}{16}$	55	.9811	49.00	47.69	22940
70	$\frac{3}{16}$	55	.9793	50.00	48.60	23340
71	$\frac{3}{16}$	50	.9817	85.00	83.05	35460
72	$\frac{3}{16}$	50	.9836	89.00	87.14	37250
73	$\frac{3}{16}$	50	.9823	85.00	83.10	35480
74	$\frac{3}{16}$	50	.9792	84.00	81.85	34940

Table No. 2 con.

Experi- ment No.	Port Opening inches	Pressure Exhausted Against Pneumo	Quality of Steam	Weight of Water Evaporated per min.	Weight of Steam pas- sing through port per min.	Velocity in Feet per min.
75	$\frac{3}{16}$	50	.9823	85.00	83.10	35480
76	$\frac{1}{4}$	55	.9842	76.00	74.50	24530
77	$\frac{1}{4}$	55	.9836	72.00	70.42	23180
78	$\frac{1}{4}$	55	.9827	74.00	72.32	23810
79	$\frac{1}{4}$	55	.9842	76.00	74.50	24530
80	$\frac{1}{4}$	55	.9850	75.00	73.90	24000



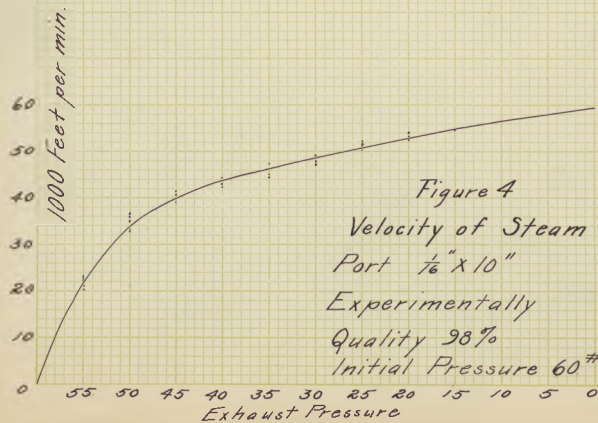


Figure 4

Velocity of Steam through
Port $\frac{1}{16}$ " x 10"

Experimentally

Quality 98%

Initial Pressure 60#

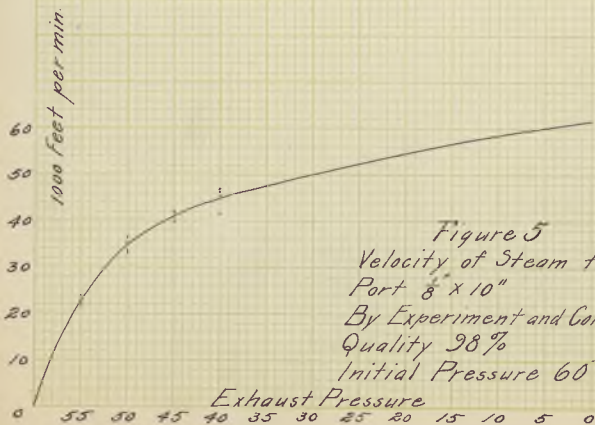


Figure 5
Velocity of Steam through
Port $8 \frac{1}{2} \times 10$ "
By Experiment and Comparison
Quality 98%
Initial Pressure 60[#]

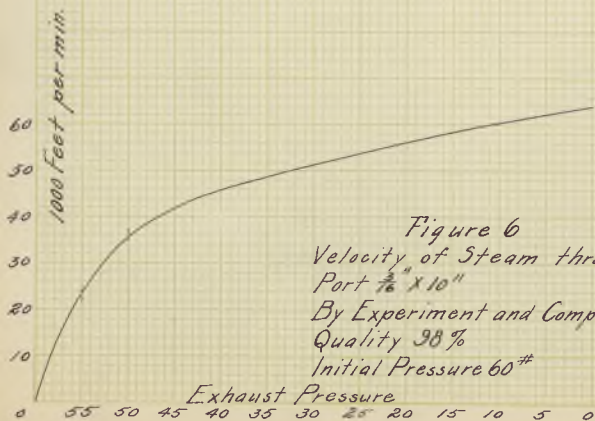


Figure 6
Velocity of Steam through
Port $\frac{7}{8}$ " \times 10"
By Experiment and Comparison
Quality 98%
Initial Pressure 60[#]

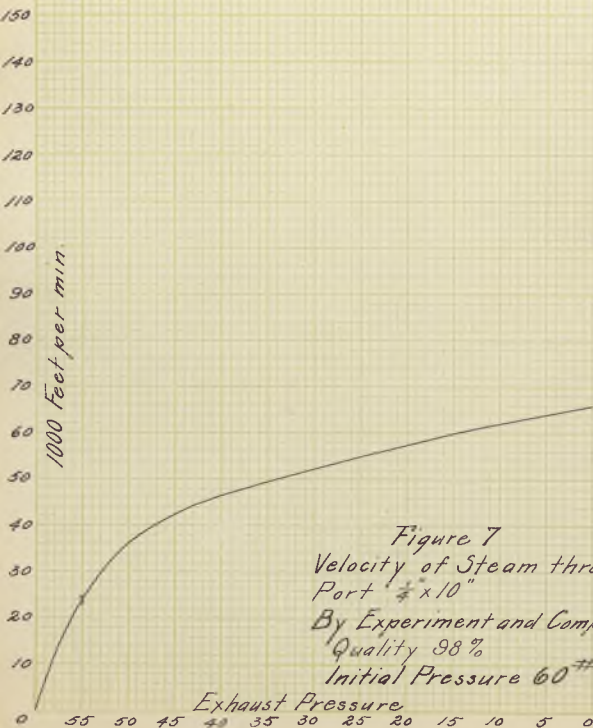


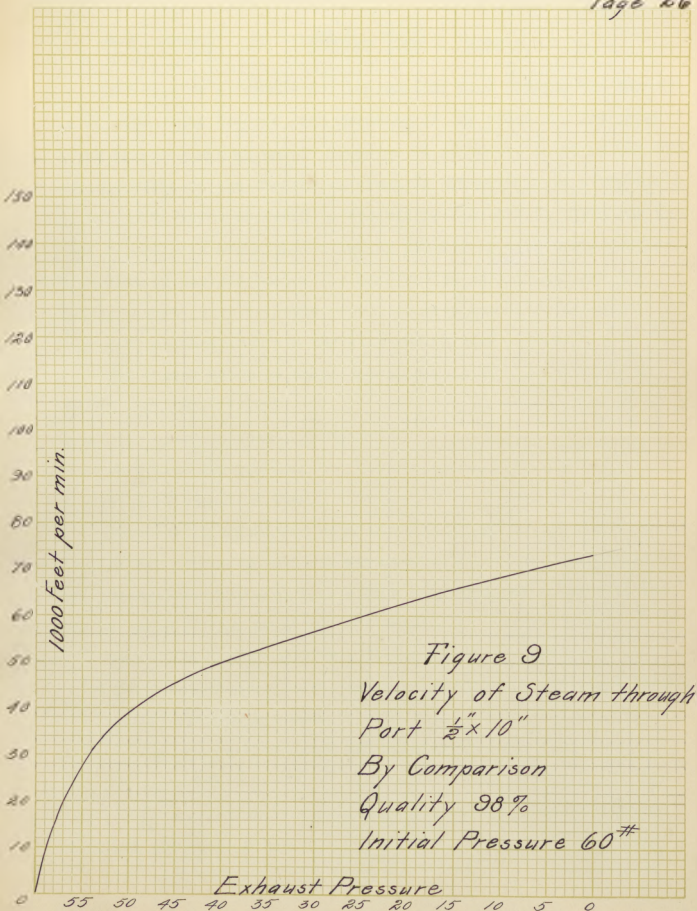
Figure 7
Velocity of Steam through
Port $\frac{1}{4} \times 10$ "
By Experiment and Comparison
Quality 98 %
Initial Pressure 60^{psia}

Exhaust Pressure

1000 Feet per min.

Figure 8
Velocity of Steam through
Port $\frac{3}{8} \times 10''$
By Comparison
Quality 98%
Initial Pressure 60[#]
Exhaust Pressure

55 50 45 40 35 30 25 20 15 10 5 0



PORT OPENING FOR DIFFERENT PISTON SPEEDS.

In deriving a formula for the area of port opening the factors to be taken into account are; velocity of the steam for the given width of port, piston speed, diameter of cylinder, point of cut off and the ratio of the lengths of crank to connecting rod. The width of the port, ratio of crank to connecting rod, piston speed and diameter of cylinder are either fixed or assumed in each engine design. The point of cut off varies for each change in the load and the the port area must be large enough to keep the steam pressure from falling more than ten per cent for maximum cut off.

The piston speed as taken for an engine is

$$V = N \times 2 \times L$$

V = piston speed in feet per minute.

N = revolutions per minute.

L = length of stroke in feet.

This piston speed varies at every point of the stroke between zero at the beginning and end and maximum speed near the middle of the stroke; hence some constant must be introduced to correct the piston speed for point of cut off taken.

The value of this constant is derived as follows:

Let x = distance piston has traveled when cut off takes place.

r = length of crank.

α = angle that crank has rotated through.

$$\alpha = \cos^{-1}(r-x)$$

$\frac{x}{2r}$ = fraction of stroke that piston has traveled through when cut off takes place.

$\frac{\alpha}{180}$ = fraction of crank circle that crank pin has traveled when cut off takes place.

If the angular velocity be taken as uniform then the constant to be used equals

$$C = \frac{180X}{2\pi\alpha} = 90 \frac{X}{\pi\alpha}$$

The port area multiplied by the velocity of the steam is equal to the piston area multiplied by the piston speed.

$$\text{Port area} = \frac{\pi d^2 c v}{4 \omega}$$

d = diameter of cylinder.

v = piston speed in feet per minute.

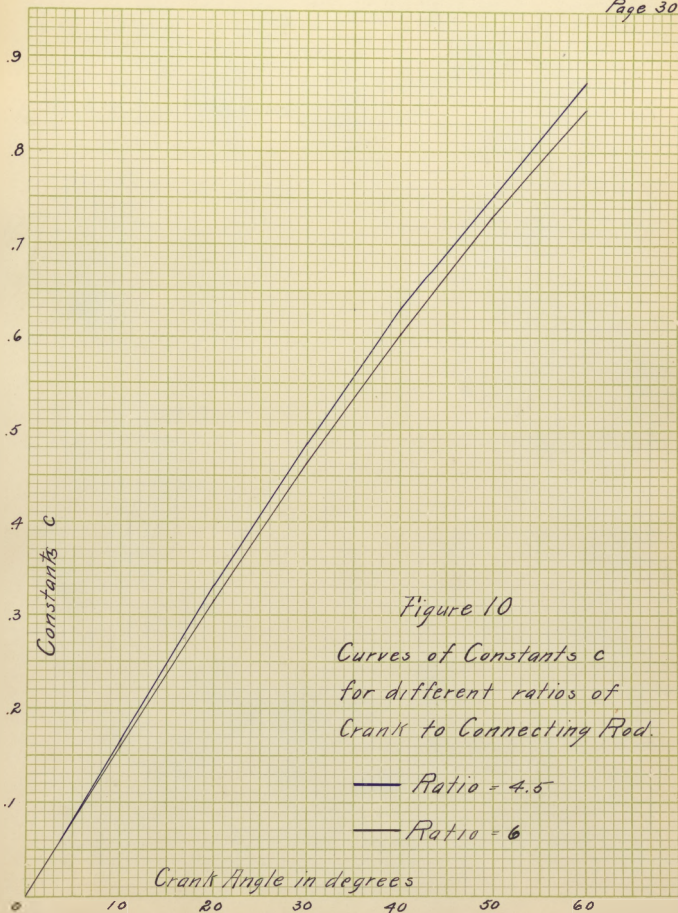
C = constant.

ω = velocity of steam in feet per minute for given width of port.

Table 3 pp 29 and Figure 10 pp 30 gives the values and curve for the constant c , for different ratio of crank to connecting rod and different point of cut off.

Table No 3

Crank Angle	Ratio of Crank to Connecting Rod							
	4.5		5		5.5		6	
	Cut off	Constant	Cut off	Constant	Cut off	Constant	Cut off	Constant
10°	.0092	.1656	.0091	.1648	.0089	.1602	.0089	.1602
20°	.0367	.3303	.0360	.3240	.0355	.3195	.0350	.3150
30°	.0809	.4854	.0796	.4776	.0784	.4704	.0774	.4644
40°	.1400	.6300	.1371	.6170	.1358	.6111	.1342	.6040
50°	.2115	.7514	.2081	.7491	.2054	.7404	.2032	.7315
60°	.2920	.8760	.2878	.8634	.2843	.8529	.2814	.8442



W. A. Fraser